BALLISTICS, NAVIGATION AND FLIGHT CONTROL OF A SPACECRAFT IN THE PROJECT OF DELIVERY TO THE EARTH RELICT SUBSTANCE – EXEMPLARS OF THE GROUND OF A SMALL CELESTIAL BODY (PROJECT PHOBOS-SAMPLE-RETURN)

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ABSTRACT *–The goal of the project is the flight of a spacecraft to Mars, landing to the surface of the Phobos, taking samples of soil and their delivery back to the Earth. The mission is planned to realize in 2005-2008 years. The increase of the spacecraft useful weight is achieved by equipping the spacecraft by electric propulsion engine. The errors in magnitude and direction of thrust do navigation more difficult. Further the spacecraft is transferred to the "observation orbit" around the Mars and then to a quasi-synchronous orbit. The spacecraft starts from Phobos after taking soil. The spacecraft is transferred to trajectory to the Earth. Effective scheme of navigation and flight control is developed which ensure, necessary accuracy.*

KEYWORDS: Phobos-Sample-Return project, relict substance of the Solar System delivery, navigation accuracy.

INTRODUCTION

The main goal of the Phobos-Sample-Return project is delivery of the relict substance of the Solar System from a small celestial body. Phopbos was selected as such one. Ballistic, navigation and motion control are important for the mission preparing and realizing.

The mission includes four phases [1]:

- Insertion spacecraft into heliocentric Earth – Mars orbit;
- Earth – Mars cruise finishing by spacecraft insertion to near Mars orbit,
- Orbital motion near the Mars and maneuvers execution, providing close approach spacecraft to the Phobos, landing to its surface and taking samples of soil, launch returned spacecraft from Phobos and flight at the waiting orbit

– Transfer spacecraft from waiting orbit to cruise orbit Mars – Earth, and entry to the Earth atmosphere at the given region of Russia.

Earth – Mars cruise phase

Following requirements was satisfied in order to Earth – Mars cruise provide: the orbital plain of the spacecraft near the Mars is coincident with the plain of the Phobos, the spacecraft flyby trajectory distance from Mars center is near with the Phobos semi-axes, the areocentric asymptotic velocity is about zero. In the cruise phase main target of the navigation and flight control is spacecraft insertion to the Mars flyby orbit with the errors not exceeded about 200 km. In order to delivery spacecraft to the Mars electric propulsion engine (EPE) is used. It operates during whole cruse phase excepting last month before the Mars approach. The presence EPE is an important specificity of the project. We know very good force field for spacecraft motion model, so it passive motion can be predict with high accuracy. EPE operate model is known not so accurate (there are significant execution errors). So new for us problem have been occurred and solved: to determine the orbit of spacecraft with EPE, motion parameters predict and there errors estimate.

The measurements will be used from three 70-meters-antennas of tracking stations in Evpatoria, Ussuriisk and Medvezhy Ozyora for navigation [2]. The measurement structure is range, Doppler shift and 3-way Doppler using at the most important stages.

The EPE-generated acceleration errors were accepted as follow: 5% for thrust value and 30 arc minutes for thrust vector direction.

The results of the error estimation of spacecraft state vector at one month before the Mars approach are about 2-3 thousands km in position and about 4 m/sec in velocity parameters. Some accuracy improving can be exceeded by estimation during the flight of the EPE operate parameters.

In order to accuracy of the orbit determination and motion parameter prediction increase sharply the EPE will be switch off month before the Mars reaching. After this during three weeks of the powerless trajectory stage, intensive tracking measurements are performed. The error estimation gives about 30 km (see fig. 1,2).

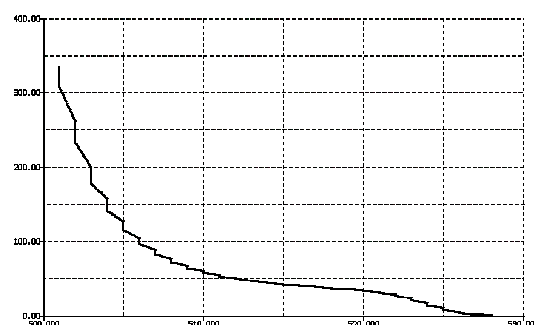

Figure 1. Estimated error of the position during last month of cruise phase

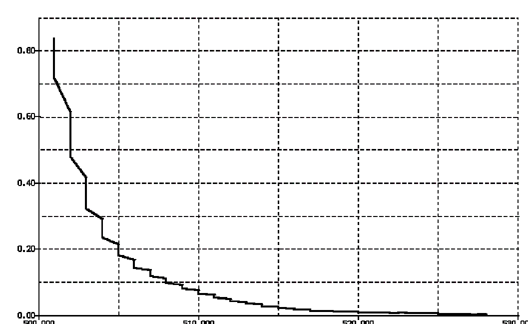

Figure 2. Estimated error of the velocity during last month of cruise phase

Before 7-10 days of Mars approaching trajectory correction is executed. Tacking into account the errors of this correction the spacecraft will be conveyed to Mars with the errors not exceeding 100 km in relativity position.

Orbital motion in the vicinity of the Mars

Main task of the Mars satellite phase is to delivery spacecraft to the space area located 40-70 km above of the given Phobos surface point. The accuracy of the delivery must be sufficient for successful operating of an autonomous system of landing (ASL) also the lighting conditions radio-communication with the Earth must be ensured. The errors of the spacecraft predicted motion relative the Phobos should not exceed of 1-3 km in position and 1 m/sec in velocity. In order to solve this complex navigation task the spacecraft is supplied by the autonomous three-parametric system of the navigation measurements. The system includes the television camera (after images processing it gives the line-of-sight angles from spacecraft to Phobos in the inertial coordinate system) and radar measurement system, for measuring of distances from spacecraft to Phobos surface). This measurements transmit from the spacecraft to the Earth and process together with the tracking station measurements in order to the spacecraft and Phobos orbital parameters improve.

The geology specialists have proposed a set of possible sites for landing. In this paper we consider one of there, which positing is defined by coordinates 330° of east longitude and –20° of latitude.

Two orbits are used to approach the Phobos: an orbit of observation and a quasi-synchronously orbit (QSO). After braking maneuver the spacecraft is inserted into the orbit of observation and the landing performs from the QSO orbit using the ASL.

The plane of nominal orbit of observation coincides with the Phobos orbital plane, and the apsis line coincides almost with the periapsis of the flyby orbit. So selection of the orbit is reduced to selection of its orbital period and periapsis values. The orbit is selected tacking into account following requirements:

– The possibility of collision the spacecraft with thePhobos due to relative positions errors must be excluded,
– The possibility must be provided to execute the periodic session of the Phobos television observation and the radar measurements of the spacecraft – Phobos range.

As such orbit of observation orbit is chosen, which semi-axis exceeds a semi-axis of the Phobos orbit of 500 km. The calculation of orbit parameters of is made in view of the following marginal errors:

Spacecraft delivery error at the time of flyby trajectory periapsis in position	200 km
Position knowledge error at this time	30 km
The execution error of the braking maneuver magnitude along the thrust	0.1%
The direction error of the braking maneuver	0.5°
Phobos ephemeris error (in position)	20 km

In an outcome as orbit satisfying to all explained requirements, orbit with the following parameters is chosen:

Orbital period	8.32 hours ±50 sec
Periapsis	9905 ± 220 km
Inclination to the Phobos orbital plane	0 ± 1.3°
Period to the Phobos approach	4 days
Period to the Phobos approach with a possibility of observation from Earth	8 days
The shortest time for which the s/c – Phobos distance is less then 1000 km	1.7 hours ± 25 min

During the orbit of observation phase a following important navigational problem must be solving. It is necessary to improve the spacecraft orbital parameters relative to the Phobos mass center and Phobos' gravitational constant. This improving provides the possibilities to predict the orbital parameters relative the Phobos in order to transfer spacecraft into the QSO with satisfied accuracy. For solution the problem following measurements are used (see table 1).

Table 1

Measurements	Accuracy
2-way Doppler shift from the tracking station in Evpatoria, Ussuriisk and Medvezhy Ozyora	0.2 mm/sec
3-way Doppler shift from the tracking station in Evpatoria – Ussuriisk and Evpatoria – Medvezhy Ozyora	0.05 mm/sec (relative error)
Onboard TV-Phobos images converted to a inertial angels	5 arc minutes
Radar spacecraft – Phobos surface range measurements	200 m

In order the spacecraft relative Phobos motion parameters estimate measurement arc is used by duration of 23 days. The measurement composition is following

Frequency of the Doppler shift measurement performance	1 time per 3 orbits
Tracking station	Evpatoria, Ussuriisk
Total measurement session number	50
Total TV session number	4
Total radar session	3

The estimated error of the predicted motion parameters at the approach time of spacecraft to the Phobos does not exceed 1.5 km for relative position and 0.4 m/sec for relative velocity. The error of the Phobos gravitational constant determination does not exceed 10 % from its magnitude.

QSO orbit have been selected to provide ASL by the high precision navigation data needed for the successfully landing. The feature of this orbit is a small distance from the Phobos (~100 km) at the whole flight time interval. This allows to TV-images resolution increase and so the measurement accuracy of the spacecraft – Phobos line-of-sight increase. Some requirements were taken into account to select QSO parameters. Firstly, the possibility should be provided to repeat the attempt of landing, if the nominal session of an ASL will not be realized and the spacecraft will remain in the former orbit. Secondly, the possibility should be provided solving of the vital important problem: to identify functionability of the laser altimeter of ASL, before the beginning its activity in the landing session. Time moment, which the onboard altimeter will switch on, is determined by the motion predict data. Its measurements allow estimate the actual accuracy of the predicted orbital parameters needed for operation of the ASL and solution accept about ASL session beginning.

The spacecraft trajectories researching have been fulfill as three-body problem (Mars, Phobos, Spacecraft) in order to QSO parameters select. As result QSO have been selected with epicycle of 50x130 km. The orbit allows provide repeated approaching spacecraft to the Phobos. The figure 3 illustrates the selected QSO trajectory and part of transit trajectory arc. The picture is given in a rotated coordinate system. The center of the system located in the Phobos mass center. The X-axes is directed from Mars to Phobos, Y-axes located in the orbital plane and directed normal to X.

The transition from the orbit of observation to QSO can execute by three maneuvers. The summarized characteristic velocity of the maneuvers does not exceed 150 m/sec. The sum of modules of two final impulses is ~ 60 m/sec.

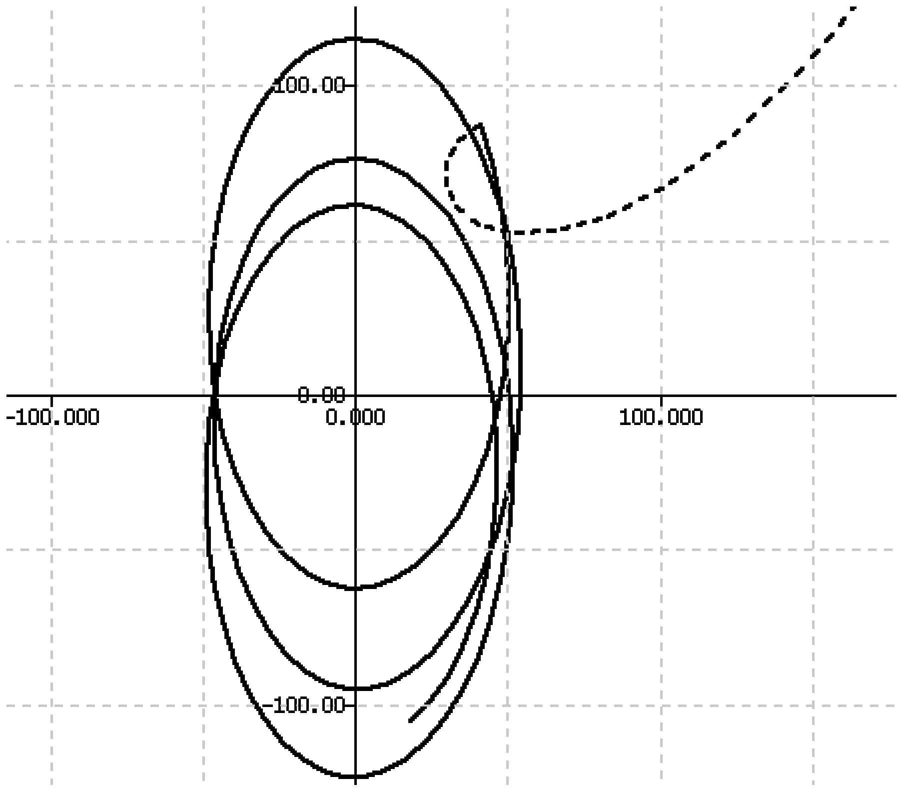

Figure 3. Quasisynchronously orbit

The covariance analysis and Monte-Carlo method has been used in order to determinate the spacecraft delivery errors into the landing area. The accuracy of the spacecraft insertion into the point under the given area depends on the predict motion errors, the Phobos gravitational constant error, the passage maneuver execution errors, time interval between the QSO beginning and landing session. Marginal delivery error at the 5th day after the QSO beginning is asymmetric and mounts in altitude under the Phobos surface 1 km in the Phobos direction and 50 km in the of the opposite direction. ASL deal successful with the errors.

As the modeling shows in order to the spacecraft parameters determinate with acceptable accuracy 4 days is required. So the time has been selected for insertion into QSO before 5 days from landing session. Following navigation measurement composition have been selected for determination and prediction of the spacecraft relative Phobos motion parameters:

- Doppler shift measurements from tracking station in Evpatoria and Ussuriisk, (one session of each station for each of 10 orbits)
- Three sessions of onboard TV Phobos observations,
- Three sessions of radar onboard Phobos measurements.

The spacecraft relative Phobos motion parameters determination using the measurements allows predict its up to one day forwards with the errors 3 km in position and 0.8 m/sec in velocity. The figure 4 shows the spacecraft trajectory projection to the Phobos surface before the landing. The trace moves from longitude 180° to the landing point with longitude of 330°.

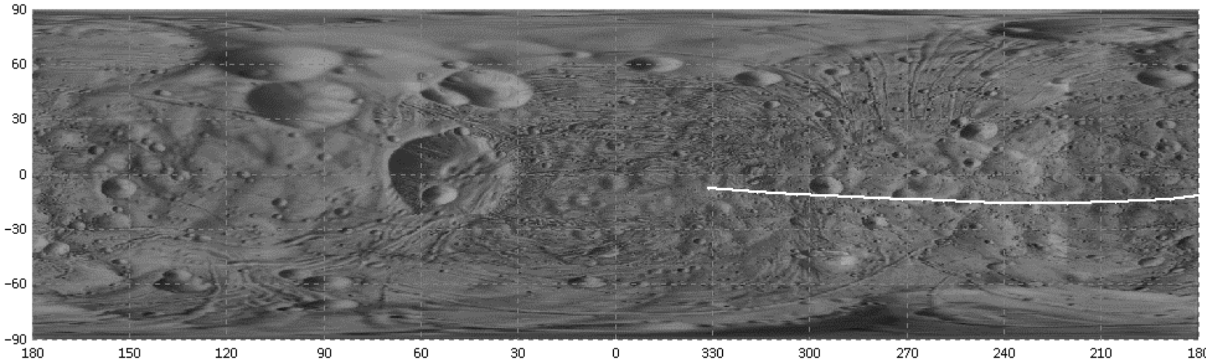

Figure 4. Spacecraft trace on the Phobos surface

The selected scheme of the flight provides the possibility of the landing time shift for 5 days. It increases reliability of the landing success realization.

Spacecraft with the Phobos soil return to the Earth

There are two possibilities to insert spacecraft into the return trajectory: The first one is released immediately after the lunch from Phobos. The second way uses the waiting orbit. The Mars – Earth cruise's time interval mounts about 9.5 months. Characteristic velocity of the transition maneuver do not exceeds of 2.95 km for the whole lunch window. This impulse stays without changes if the waiting orbit is used, bat it is divided into parts: 0.4 km to insert into waiting orbit and 2.19 km to transit into cruse Mars – Ears trajectory. The maximal execution errors of the maneuvers shouldn't exceed ±1% in the velocity magnitude and ±2° in the direction.

Main task of the Mars – Earth cruise phase is delivering of the reentry spacecraft (RSC) to the given landing polygon of Russia and its sure discovering. To satisfy there requirements the delivery uncertainty must be less ±30 km in position and the motion prediction errors must be less ±5 km. Four trajectory corrections are provided for the Mars – Earth cruse phase:

- The 1st about 10 days after the lunch to the Earth
- The 2nd about 5 months after the 1st correction maneuver
- The 3rd about 3 months before spacecraft encounter with Earth
- The 4th from 72 to 12 hours before spacecraft encounter with Earth

The flight path angle at the atmosphere interface mounts 39°±6°

The measurement composition at this phase is following

Before the 1st correction	2 times in a day from the 2 tracking stations (Evpatoria, Ussuriisk)
Between 1st and 3rd corrections	1 time per 4 days from the 2 tracking stations (Evpatoria, Ussuriisk)
Between 3rd and 4th corrections	1 time per 2 days from the two tracking stations (Evpatoria, Ussuriisk)
After the 4th correction	1 time per a hour from the all three tracking station (in visibility)

The errors of the spacecraft delivery to the Earth and the motion prediction errors are contained in the table 2. Also the table contains expected magnitudes of correction maneuvers

Table 2

Correction number	Day number of flight	Maneuver magnitude (km)	Motion prediction error	Delivery error
1	12	146	12400	421000
2	165	15	50	20000
3	225	1.5	87	700
4	286	9.5	5	30

The accuracy of the spacecraft delivery to the Earth depends greatly on the errors of the correction impulses magnitude.

The choused scheme of the spacecraft deliver to the Earth solve the task of the RSC landing to the given polygon tacking into account trajectory measurements errors, transit maneuver errors from Mars satellite to return cruise trajectory and execute errors of the corrections.

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